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ABSTRACT

Since the mid-1960s a new approach has dominated American research in the area of mathematics education -- information-processing theory. The author examines several examples of research in this new tradition and sketches the general features of an emerging information-processing psychology of teaching. Information-processing studies that employ descriptions of behavior, systematic introspection, and computer simulation to develop and test theories of mathematical learning and problem solving are described. (Author/MK)

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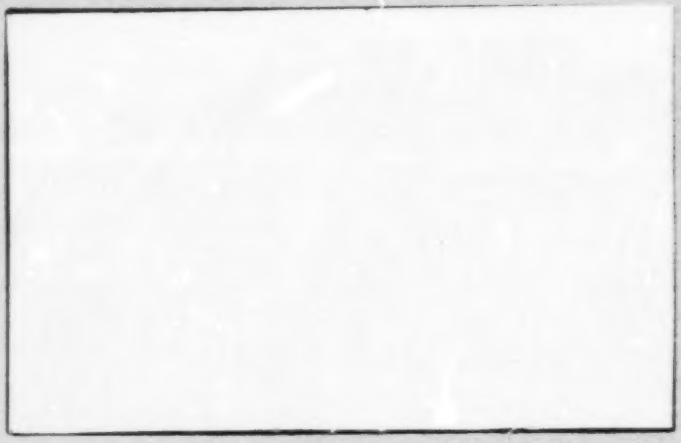

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PSYCHOLOGY AND MATHEMATICS EDUCATION REVISITED

Lee S. Shulman
with Janet Shroyer

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Abstract

Since the mid-1960s, a new approach has dominated American research in the area of mathematics education -- information-processing theory. The author examines several examples of research in this new tradition and sketches the general features of an emerging information-processing psychology of teaching. Information-processing studies that employ descriptions of behavior, systematic introspection, and computer simulation to develop and test theories of mathematical learning and problem solving are described.

Psychology and Mathematics Education Revisited[1]

Lee S. Shulman
with Janet Shroyer[2]

During 1968, Professor Edward Begle invited me to prepare a chapter on the psychology of mathematics instruction for a yearbook he was editing. I protested that, while I had been engaged in studies of teaching and learning generally, with special reference to problems of learning by discovery, I could claim no special expertise in the area of mathematics instruction. Begle responded that this was perfectly acceptable. Motivated more by temerity than wisdom, I proceeded to prepare such a chapter, which appeared in the subsequent NSSE Yearbook on *Mathematics Education* (Shulman, 1970). In the ensuing years the chapter has been characterized in many ways, most accurately as an exposition which dealt far more with psychology than with mathematics, a flaw clearly attributable to the limitations of its author.

In the years since that chapter, I have been examining principles of teaching in the natural sciences and medicine. With a group of colleagues, I have been most vigorously conducting empirical and theoretical studies in the mysteries of medical diagnosis and decision making. It was thus a surprise (and a bit anxiety-provoking) to receive the invitation to participate in this working group. The collaboration of Janet Shroyer, who has maintained a continuing involvement in mathematical learning and

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[1] An earlier version of this chapter appears in Forschung zum Prozess des Mathematiklerners, Institut für Didaktik der Mathematik der Universität Bielefeld, 1976 (proceedings of a conference held in Bielefeld, West Germany).

[2] Lee Shulman is a professor of educational psychology and medical education and the director of the Institute for Research on Teaching. Janet Shroyer is an instructor in the Department of Mathematics at Michigan State University.

teaching, significantly reduced that anxiety. Thus, with this disclaimer regarding my prolonged absence from the problems of mathematical learning, I shall proceed.

State of the Art in the 1960s

I intend first to summarize the major propositions of the paper I wrote nearly eight years ago (Shulman, 1970). At the time it was written, that paper represented for me the major psychological influences on the problems of mathematics curriculum and instruction. Both its emphases and its serious omissions reflect the particular obsessions of educational psychology during the middle 1960s.

The NSSE chapter presented a single instructional issue as the basis for dividing the field into its major constituents. That issue, which had been a significant interest of mine for several years, was learning by discovery. Two eloquent advocates of guided learning -- Robert Gagné and David Ausubel -- were contrasted in their positions on the learning of mathematics with two equally assertive defenders of discovery learning -- Jerome Bruner and Jean Piaget. Employing somewhat stark caricatures of the opposing positions, the underlying assumptions, principal emphases, and instructional implications of these views were explored, with particular emphases upon the positions of Gagné and Bruner, each of whom had influenced rather directly the approaches to mathematical learning in the United States. The parochialism of the analysis was that of both psychology and North America. This dual parochialism will be equally evident in the present manuscript.

In the 1969 chapter, the neo-behaviorism of Gagné was contrasted with the cognitive developmentalism of Bruner. Although Bruner

typically cited the work of Piaget as evidence in support of his pedagogical assertions, a rift had emerged between Geneva and Cambridge. To this outside observer those disagreements had few educational implications. They sounded very much like members of the same church, praying in adjoining pews while debating over details of theology or ritual. Ausubel was a bit of an anomaly, since he insisted on thinking about learning in a cognitive manner, while advocating a highly guided method of teaching. Nonetheless, the general framework of the chapter treated schools of psychology as a set of starting points for educational theory, moving a generation of psychologists nursed on the debates among Thorndike, Skinner, and Hull, among others, to a more contemporary concern for their modern replacements. The emphasis of the exposition was exclusively on the influences of these varieties of psychological theory on the development of curriculum or the organization of instruction and learning. Where was the *teacher* in this classroom so fully populated with curricula and learners? Alas, nowhere to be found.

Current Directions

In the period since the late 1960s, significant changes have taken place in both psychology generally and the psychology of instruction in particular. A new mainstream has emerged to replace the older battleground of behaviorism and cognitive psychology -- information-processing theory. This variation of cognitive psychology has emerged as the dominant theoretical view of most educational and learning psychologists. Most dramatically, Robert Gagné (1974), whose writings could be suitably employed to represent educational neo-behaviorism in the earlier chapter, has now announced himself as espousing an information-processing view. His primary antagonists, Ausubel and Bruner, are no longer active in

educational research. A new generation of educational information-processing psychologists has emerged to replace them.

A second important change that has taken place since the late 60s is a renascence in the field of research on *teaching*, rather than exclusively on learning. Moreover, there is a current movement toward applying that same cognitive information-processing approach to the phenomena of teaching as has been applied to the processes of learning, perhaps presaging an eventual, though still remote, unified information-processing theory of teaching *and* learning.

Roots of Information-Processing Theory

In the mid-1950s, a series of publications emerged which, though produced quite independently, heralded a revolution in contemporary psychological theory. With little elaboration, these are some of the events which contributed to the creation of a totally new Zeitgeist in American psychology.

-- Bruner, Goodnow, and Austin (1956) published a research monograph entitled *A Study of Thinking*, combining the attempts to characterize strategies of concept learning with applications of decision theory in order to discuss problems of memory limitations and cognitive strain. Use of the naughty word "thinking" in the title is noteworthy.

-- George Miller (1956) discussed the "magic number seven plus or minus two" as an estimate of the limitations of short-term memory, introducing the notions of bits and chunks to the psychology of learning and memory.

-- Noam Chomsky (1957), a young linguist at Massachusetts Institute of Technology, published the remarkable *Syntactic Structures*, the first systematic presentation of transformational grammar and his theory of linguistic competence, a theory destined not only to rock the field of linguistics, but that of psychology as well.

-- Three behavioral scientists at Carnegie Technical Institute in Pittsburgh produced a computer simulation capable of proving theorems from Whitehead and Russell's *Principia*. Newell, Shaw, and Simon's (1958) problem-solving programs not only imitate human intelligence, but even invent theorem proofs that are novel. In their work, they lay the ground rules for using computer simulations to test and refine theories of human information processing.

-- The aforementioned books and papers were finally summarized into a single theoretical position regarding thought, action, and language. This general statement of the information-processing position was *Plans and the Structure of Behavior*, by Miller, Galanter, and Pribram (1960). It continues to serve as a significant theoretical statement today, more than a decade and a half later.

-- The work of Jean Piaget had long antedated the cognitive information-processing revolution of the mid-50s, but had never before taken root solidly in the soil of American psychology and education. The cognitive information-processing revolution created an intellectual climate which made the reading of Piaget on the North American continent not only possible, but influential and meaningful. In 1961, J. McVicker-Hunt's book, *Intelligence*

and Experience, demonstrated that Piagetian theory and information-processing theory could be synthesized into a single perspective on the role of experience in the development of intelligence.

Ironically, while these cognitive concepts had a profound impact on the kinds of mathematics and science *curricula* produced during that period (lending credibility to the notions of problem solving, discovery, and early readiness which permeated those efforts), experimental research on learning, thinking, and teaching remained rather traditional and neo-behavioristic. (It is worth noting that during this period the principles which dominated the approaches to instructional evaluation, classroom management, and environmental design were highly behavioristic, even Skinnerian. Thus elementary and secondary school curricula emphasizing discovery and conceptual invention were evaluated using behavioral objectives and task-analytic reductive frameworks in classrooms managed by teachers employing behavior modification.)

The cumulative impact of this revolution in psychology is perhaps best expressed by one of the leading spokesmen of behaviorism, Gregory Kimble (1975). In reviewing the most recent edition of that bible of learning theory, Hilgard and Bower's (1975) *Theories of Learning*, Kimble remarks on the changes in his discipline:

> How far we have come in the past ten years; that the white rat and the pigeon no longer provide the majority of our data, that complex mazes are rarely used these days, that S-R has been deposed as king of the theoretical hill, that 'mind' is no longer a dirty four-letter word, and that petty bickering over small points in little theories no longer describes the standard mode of intellectual interaction among the psychologists of learning (p. 613).

Having established the transition of American psychology from neo-behaviorism to cognitive information processing, I can illustrate the shift by briefly describing the changes in one psychologist's

position. Robert Gagné has become closely identified with a perspective on the conditions for learning that treats all forms of learning as hierarchically organized in relation to one another, with classical and operant conditioning as the foundation for the hierarchy and problem solving as its peak. From his perspective, any form of learning could be reduced to its components, which were sub-tasks, and these could be systematically taught in a guided fashion to ensure learning. Over the past 10 years there has been a metamorphosis in that position, transforming a neo-behaviorist into an information processor, an advocate of a single model of learning into one who describes at least five distinctly different kinds; a proponent of the primacy of hierarchically organized intellectual skills into someone who now asserts that cognitive strategies serve as the executive processes which control intellectual skills, and these strategies may well be learnable only by discovery. The details and implications of this change in Gagné's position cannot be discussed adequately here, but they may well be profound. (It is likely that these changes which, to an American psychologist, seem comparable in magnitude to a religious conversion, will strike the European educator or psychologist as trivial indeed. Despite the shift in theoretical predilection, Gagné remains, like most American educators, committed to the *design* of instruction even when discussing discovery.)

Examples of Information-Processing Research

What is an information-processing perspective on human learning and thinking? It emerges from a conception of cognition which treats learners as goal-seeking problem solvers whose ability to deal rationally with their environment is profoundly constrained by the intrinsic limitation of their capabilities for processing information. These limitations are present in many stages of the cognitive process,

including attention, selective perception, and most significantly, short-term memory and encoding for long-term memory storage and retrieval.

Thus the "bounded rationality" (Simon, 1957) of the human information processor results in his/her constructing a simplified model of real problem situations in order to cope with them. To understand why people approach problems in a particular way, it is necessary to understand their goals, the major characteristics of the *task environment* in which they work, and the transformation of that task environment into a cognitive *problem space* which reflects the limitations of their *invariant information-processing capacities*.

The manner in which one approaches problems of mathematical learning from this perspective is reflected in the work of Greeno (1976). Greeno has been studying the processes used by students proving triangles congruent. For the study, 24 protocols of successful proofs were collected from five students enrolled in a high school geometry class. The students were asked to talk their way through the proofs and respond to questions which the examiner might ask to help clarify his understanding of their thinking.

Through the detailed descriptions collected from the student reports and the careful examinations of the problems and their possible solutions, some fundamental processes which might have been capable of generating the protocols were postulated. In this situation, the general strategy that was most apparent was that of searching for pairs of congruent parts until a recognizable pattern for proving triangles congruent became evident. This delay in setting a goal to use a particular theorem is not a familiar routine to the means-end analysis (Newell & Simon, 1972) identified as the strategy in many of the tasks

already studied. Once determined, all of these details were given representation in a model that was expressed in language appropriate to the problem.

The next stage of the investigation was the development of a computerized problem-solving system expected to simulate the performance of the students. To accommodate the strategies or processes extant in the models of student performances, the computer program was provided with three categories of processes: (1) problem-solving strategies similar to the means-end analysis mentioned earlier; (2) a propositional inference capability, which enables the system to use inferential statements to generate further information; and (3) pattern recognition, which tests for the presence or absence of particular features of the figures. It was pattern recognition that enabled the program to *delay* the choice of which theorem to use proving triangles congruent until sufficient information was available. Despite these capabilities, the computer system did not possess the flexibility available to human problem solvers, though it did realistically approximate their performances.

It is this computer program which constitutes a theory of geometry congruence proving, but it is the techniques of this study which illustrate the characteristics of an information-processing approach to research. What are these characteristics? First, the procedure Greeno used for collecting the information is often called process tracing (Shulman & Elstein, 1975). Second, the protocols were coded into a language and interpreted to represent the state of the problem and the processes used. This was all combined into a production system that was capable of generating the performance of the subjects. Third, a computer program was constructed to execute a production system simulating the human problem solver. Fourth, a comparison was made between the protocols

generated by the computer program and the protocols made by the human subjects to ascertain the adequacy of the theory.

Greeno's investigation was but one of many studies conducted under the rubric of problem-solving research -- a field in need of a theory of mathematical problem solving. Such a theory must contain first, a description of how different kinds of problems are solved, and second, a taxonomic or logical analysis of the interrelations among problem types (Shulman & Elstein, 1975). Confronting this challenge, Greeno (1978) has suggested a typology -- not yet a taxonomy -- of problems. Although he acknowledges that many problems cannot be classified as only one type, Greeno has, on the basis of the task demands, identified three types of problems along with the skills necessary to solve each type.

Description of Greeno's typology is inappropriate here, but the categories easily accommodate many problems of interest to the mathematics educator. Tasks which learners often face include concept attainment, rule or classification recognition, theorem proofs, and complex calculations. Greeno's typology supplies direction for further research.

In addition to identifying the processes or strategies students use in a particular task environment, what are some of the values of this research type to mathematics educators? It may have implications for mathematics instruction similar to those the medical inquiry studies (Shulman & Elstein, 1975) have had for instruction of medical students in the arts of diagnosis. Students adept at solving mathematical problems may be compared with physicians skilled in diagnosis. Knowing how "experts" behave has certain clear implications for how teachers assist students to perform expertly. Medical students, for example,

have traditionally been instructed to withhold forming hypotheses until all the evidence is collected. However, unlike the congruence provers, early hypothesis generation was found to be a universal characteristic of the sample of physicians and problems studied, and this awareness led to some changes in training medical students in diagnosis. Similar understanding of the processes of "expert" mathematical thinking may lead to new insights regarding mathematics teaching.

Another technique which falls within the scope of information-processing research is directed at the isolation of a single cognitive process in mathematical learning. Groen and Parkman (1972), Groen and Poll (1973), and Woods, Resnick, and Groen (1975) have used response latencies -- differences in elapsed time -- to infer processes used in solving single-digit addition and subtraction problems. These are tasks where there is little behavioral or introspective evidence on which to produce protocols as in process-tracing studies such as Greeno's. A classical technique, chronometric analysis, is based on the assumption that when a process can be broken down into identical steps, counting by ones in this case, reaction time will be a linear function of the number of counts needed to reach the answer. By collecting the latencies for a number of subjects solving a variety of problems and comparing the regression lines of possible processing models, the best fit suggests which model is most appropriate. Addition tends to be performed by setting the "counter" to the larger number and counting up, but subtraction requires a more heuristic approach -- counting up from the smaller or down from the larger depending on which is more efficient. Yet there are deviations from the regression lines, suggesting alternative procedures for special cases such as

recognizing doubles or the additive identity, and shifts in choices of processes suggesting a developmental trend. Response latencies were also used in a study by Rosenthal and Resnick (1974) to infer processes employed for correctly solving different classes of problems involving three numbers presented in verbal form but differing in order of mention, identity of unknown, and action verb.

There are several additional types of research on mathematical learning which reflect the information-processing influence, but do not lead to computer simulation. The shift in approach to studying mathematics education is evident in the work of Resnick at the University of Pittsburgh Learning Research and Development Center. Having begun work on an elementary mathematics curriculum by building hierarchies of tasks, Resnick (Resnick & Glaser, 1975) is now applying information-processing procedures and constructs to the study of problem solving.

Arguing that intelligence is the ability to solve problems, Resnick, Glaser, and collaborators have been studying what can be termed invention-problem solving, focusing on the mechanisms operative when in the absence of complete instruction, a person must "invent" a new solution to a problem by assembling previously learned skills. Resnick and Glaser have a generalized model (in flow chart format) to explain the behavior of problem solving that includes three classes of processes: (1) problem detection -- the awareness that a route to the solution is not available; (2) feature scanning -- looking for cues and attempting to find a match between previously acquired knowledge and the task environment; and (3) goal analyses -- redefining of goals and inventive routines to accomplish them.

To explore the behavior of the children who have been trained in the necessary skills but need to make transformations or inventions

before their skills can be applied, two problems were used: (1) finding the area of a parallelogram and (2) adding with multidigit numbers when "carrying" is required. A training procedure was derived from an analysis of the information-processing steps required to build a simulation of the problem-solving behavior. In general, the likelihood of invention was increased when strategies for planning ahead and considering alternative goals were incorporated.

Thus far I have demonstrated that an information-processing approach can employ introspective accounts of problem solving to generate a model of the cognitive steps employed by a subject, subsequently elaborating upon or testing the model through computer simulation. I have also observed how information-processing *theories* lead to particular kinds of task analyses, which break down the stages of information processing necessary to perform a task. These task analyses can then be tested experimentally with procedures such as measurement of response latencies, or in instructional experiments employing as independent variables alternative conceptions of the strategies which ought to facilitate problem solving. Simon (1975) has been particularly interested in the description and modeling of these strategies.

If strategies can be adequately represented, then instruction can be planned to enhance the mastery, workings, selection, or retrieval of these strategies when needed by students. In this tradition, Mayer, Stiehl and Greeno (1975) conducted a series of studies to investigate which instructional variables influence the outcomes of learning. The research is directed by information-processing conceptions of that learning. The cohesiveness of these studies, quite rare in educational research, is brought about by continued use of the same task involving the learning of some probability concepts.

One of the more important revelations, though not unexpected, was the indication of the need for mechanisms to receive material, to make available related previous experience to activate an assimilative set based on previous experience.

Parallel efforts concerning the relation of prior experience in mathematics learning can also be seen in the work of Lesh (1976) as he explores the meaning and use of Ausubel's advance organizers with college students learning finite geometries and groups, and with elementary school children learning motion geometry.

Information Processing and Piagetian Studies

I cannot discuss the use of information-processing approaches without referring to the exciting marriage of those methods and concepts with the concerns of Piagetian studies.

Within the Piagetian or developmental tradition it is worth commenting on the potential contribution of information processing in examining the transitions of cognitive development. Simon (1972) advocates describing performance models of various tasks in order to trace their changes over time and determine the mechanisms that produce them. Examples of this modeling for class inclusion and weight seriation tasks can be found in Klahr and Wallace (1972) and Baylor and Gascon (1974). The expectation is that the research methods of information processing might bridge the gap between the hypothetical structures and processes of Piaget's theory and the levels of performance exhibited in the growing body of empirical studies.

Comparing a Piagetian logical model for class inclusion with an alternative information-processing model, Wilkinson (1976) found support for the argument that inclusion errors result from the problem-solving strategy employed rather than from the logical deficits of a preoperational

child. One strategy proposed for solving class inclusion problems is a counting procedure which forbids double-counting and seems to occur in children who have yet to become automated counters. Having postulated two strategies, the second allowing for more than one counting, Wilkinson ran a series of three experimental studies to determine whether the actual performances matched those predicted by logical constraints or the choice of processing strategy.

Concerned with children's causal reasoning but wishing to separate capability from possible learned responses, Siegler (Note 1) used an apparatus unfamiliar to the children to explore their causal reasoning powers. Their outward behavior suggested developmental differences, so Siegler constructed a model of the production system, presenting different versions of the basic task to tease out which processes might account for the differences -- whether misencoding, discerning relationships, or varying standards for inference. Results were most interesting since the developmental differences seemed to be due to the ability to overcome the distracting influences. Developmental differences on tasks such as conservation, seriation, class inclusion, or probability learning have had various explanations, but Siegler appears to have developed a procedure that allows for testing competing theories by using what he labels interactional designs -- changing one aspect of the task at a time until the critical features are displayed.

A common thread emerging from all these studies is the centrality of an understanding of the *task* for understanding of the intellectual processes needed to perform the task. There is a tradition growing ever more powerful in psychology, traceable at least from Egon Brunswik, and including diverse contemporary scientists such as Herbert Simon, Peter Wason, and Robyn Dawes, which emphasizes the manner in which human problem solvers accommodate themselves to the demands of tasks.

Research on Teaching

It was observed earlier that among the serious flaws of the Shulman (1970) chapter, the most serious was that the centrality of *teachers and teaching* in the analysis of school learning was ignored. Were that chapter to be written today, it would not suffer from the same fault.

The conception of teaching I would propose grows out of an information-processing perspective. Rather than repeat what I have already written elsewhere, I call attention to the following materials for an elaboration of that perspective:

Shulman, L.S., Psychology of school subjects: A premature obituary? Journal of Research in Science Teaching, 1974.(See especially pp. 333-335.)

Shulman, L.S., & A.S. Elstein. Studies of problem solving, judgment and decision making. In F. Kerlinger (Editor), Review of Research in Education, III, 1975. (See especially final section on implications for research on teaching.)

National Institute of Education, Teaching as clinical information processing, Research planning panel, L.S. Shulman, Chairman.

Reference Notes

1. Siegler, R.S. An information processing approach to children's causal reasoning. A paper presented at SRCD Convention, Denver, Colorado, 1975.

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